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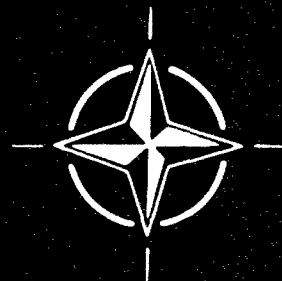
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Standardisation of Impact Testing of Protective Helmets

A Working Group Report

Edited by
D.H.Glaister

NORTH ATLANTIC TREATY ORGANIZATION



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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
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This Report was prepared at the request of the Aerospace Medical Panel of AGARD.

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STANDARDISATION OF IMPACT TESTING OF PROTECTIVE HELMETS

INTRODUCTION

Early in 1972, a Working Group was set up under the auspices of NATO/AGARD Aerospace Medical Panel. Its brief was to consider standardisation of biodynamic impact testing with special reference to helmets, seats and harnesses. The Working Group first met on 29th May, 1972, in Brussels, and areas were defined where standardisation was required between NATO's member nations. One of these areas, the testing of protective helmets for aircrew, was considered particularly appropriate for consideration, for protective helmets were worn by various aircrew to perform identical functions, yet were designed to widely differing standards, or to no standard at all.

The present paper was initially researched and written by the Working Group's Leader, and subsequently discussed at meetings and circulated for comment. The final agreed product 'Standardisation of Impact Testing of Protective Helmets' attempts a classification of currently used test procedures, and proposes a compromise approach which could form the basis for agreement within the NATO membership. In addition to impact protection, penetration resistance and helmet retention, it specifies requirements for blast protection, maximum all-up weight and location of a helmet's centre of gravity.

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1. IMPACT ATTENUATION

When an unprotected head is struck by a solid object, a very high peak force is transmitted to the skull and brain, but this force lasts for a very brief time, one millisecond or less. If the head is protected by a helmet which incorporates an energy absorbing system, such as a rigid foam liner or frangible shell and tape suspension, then the impact is prolonged and the peak force developed is reduced. Protection is attributed to this reduction in peak force, and to conversion of kinetic energy to other forms of energy such as heat or noise. Furthermore, if all the energy of the impact is absorbed, there will be no bounce and the overall velocity change, and hence energy transmitted to the head, will be at a minimum. Finally, the helmet shell acts to spread localised loads by resisting penetration by sharp objects.

Helmets are tested in the UK and US by applying predetermined impacts to one or more points on the shell, with the helmet mounted on a wooden or alloy headform. Impacts are achieved by dropping a weight onto a rigidly mounted headform, the headform may be pivoted to swing away from the line of impact (intended to simulate neck movement), or a helmeted headform may be dropped onto a rigid anvil. The struck surface may in each case be flat or hemispherical. The force transmitted to the headform is measured from a load cell in its base, or in the base of the anvil, or from an accelerometer firmly mounted on the dropped weight (force equalling mass times acceleration).

Interpretation of results is based, in the UK, on the assumption that a force in excess of 22.3 kN applied for even a few milliseconds is likely to lead to fatal concussion (i.e. BS 1869:1960), though this value has been brought down to 19.6 kN in later standards (BS 2001:1972). Differing degrees of protection are obtained by varying the impact energy. In the US, standards are based upon the Wayne-State curve which relates impact force required to produce brain damage to duration of impact. Thus, a headform deceleration of 400 G is allowable provided that it lasts for less than 2 msec, but for impacts lasting 2-4 msec the limit is reduced to 200 G and for those exceeding 4 sec the

limit is 150 G. With a dropped headform carrying a 1.5 kg helmet, these accelerations correspond to 25.5, 12.7 and 9.6 kN respectively.

Lower criteria have been adopted for industrial helmets. For example, the German DIN 4840 standard takes 500 kp (4.9 kN) as the maximum allowable transmitted force, whilst the ANSI Z-89 takes a value as low as 386 kp (3.8 kN).

Information currently available from other NATO armed forces is that the German Air Force accepts the standards laid down by the country of helmet manufacture (i.e. UK or US standards), though DIN standards exist for helmets for vehicle users, whilst France makes helmets for her Air Force, but has no standard for impact attenuation. Canada also makes use of the US Standards.

Details of all the standards known to be in use are set out in Tables 1, 2a and 2b. Whilst the US considers that 'the basic problems of head protection are common to most of interested (consumer) groups) and attempts one standard for all (i.e. Snell:1970), the UK applies less stringent standards for users subjected to potentially lesser impacts. It also appears that UK and US standards are presently diverging, for BS 2001:1972 anticipates deletion of the rigid headform technique, whilst the USAF apparently favour this technique to the eventual exclusion of the swing-away arm method. Unfortunately, correlation of these two techniques is made difficult by the variable coefficient of restitution exhibited by different helmets (Rayne, 1969).

The two US standards (ASA and Snell) have now been combined into a single American National Standards Institute standard, Z90.1-1971, but this document has been pre-empted by the issue of the US Department of Transportation's Standard, DOT 218 (Table 2b). This will become the standard used in the United States for all road users' helmets for the indefinite future. However, at present, no headforms are available for standard 218 and, undoubtedly, ANSI Z90. 1-1971 and the Snell Memorial Foundation standard will continue to be used for some time. Table 3 compares ANSI Z90, which is essentially the former ASA Z90 without the swing-away headform option, with a prediction of the form which BS 1495 is likely to take when revised. This table also gives comments concerning differences between the two standards. A major difference is that helmet weight adds to the energy of the impact in the US test, so that heavy helmets are penalised. Thus a helmet weighing 1.5 kg increases the impact energy for a flat anvil from 89 J to 116 J.

Assuming a head weight of 5 kg, a deceleration of 400 G corresponds to a transmitted force (as specified in current UK standards) of 19.6 kN. There thus appears to be good agreement as to the maximum peak force to which the head should be submitted, though this is hardly justified by the current state of knowledge concerning head injury mechanisms (i.e. see Swearingen, 1971).

Other significant differences between the two standards concern the manner in which impacts are applied, the UK calling for a single massive impact against a flat anvil, whilst the US requires eight lesser impacts to four separate sites, using a hemispherical as well as a flat anvil. A consequence is that the UK standard can be met by the use of an energy absorbing system which is destroyed on impact (torn suspension tapes and fractured shell), but this helmet could fail if required to absorb a second impact. By contrast, the US standard favours the use of a rigid foam energy absorber of which only a fraction is used up by each impact. Such a system would probably fail the single more massive impact test employed in the UK standard. The basic question which requires answering here is the relative frequency of single and multiple impacts in service usage of helmets, and how massive these impacts are. A study which has been going on at IAM Farnborough for some time (Glaister, 1974) should help here, and it is understood that a similar study has recently been initiated at Fort Rucker. Similar information is also urgently needed from the other NATO armed forces.

Given this information, there seems no eventual bar to agreeing upon a common standard for impact protection and test methods to be used for all helmets worn by NATO armed forces, for the other differences are relatively minor and could either be eliminated, or shown to be insignificant. For example, it appears that there is fair agreement about the level of transmitted force (or head acceleration) which should be accepted in a head impact, but currently a great disparity concerning impact energy requirements for helmets. Since current standards fix the input parameters the test results are not comparable. Furthermore, both UK and US standards apply pass/fail criteria and say nothing about the actual level of protection afforded by a particular helmet. In view of these shortcomings, it seems logical to adopt a test procedure recently used in the evaluation of protective helmets for mountain climbers (Schubert, 1974). In this test the acceptable transmitted force was fixed (800 kp or 7.85 kN) and the input energy required to achieve this figure was determined for single and repeat impacts on a total of six test specimens.

For military use it is suggested that the acceptable level of transmitted force be taken as 20 kN, and that a dropped headform rig is used so that the impact sites can be varied readily to include the front brim and occipital regions as well as the crown. Whilst such testing would involve more test specimens initially, subsequent batch testing and tests on conditioned helmets could be carried out at a single critical impact level. The improved data obtained, however, would prove of immediate value to all nations by reference to current standards and would allow the best helmet to be selected for any particular application.

A further problem concerns the standardisation and calibration of impact test equipment. Different devices currently used can yield different results even when working to the same standard. For example, a change of transducer to one of different band-pass characteristics can markedly modify the measurement of a peak force. A standard for minimum performance characteristics of electronic components should, therefore, be used in impact work, and that issued by the Society of Automotive Engineers (Standard J 211a) could form a basis for discussion or agreement. Thus, headform forces would have to be measured to within ± 0.5 dB at 0.1 Hz, to within +0.5 and -1.0 dB at 1,000 Hz and to within +1 and -4.0 dB at 1,650 Hz. Thereafter sensitivity would fall off at between 6 and 24 dB per octave. Also specified would be the range and frequency of calibration signals.

In the United States, the compatibility of test results from different centres has been improved by the circulation, at specified intervals, of a test piece of known impact characteristics (a multiple elastomer programmer, or MEP). It has been shown, however, that adequate accuracy of calibration may be achieved by impacting plasticine cones and then integrating the recorded force-time history to give a velocity change which can be compared with the calculated or measured impact velocity (Rayne, 1969; Glaister, 1973). Agreement on such a simple test procedure should be readily obtained.

2. PENETRATION RESISTANCE

The individual methods used by the UK, US, Germany and France for evaluating the penetration resistance of protective helmets are summarised in Table 4. The most significant difference is whether the helmet is tested intact (latest BS and ANSI tests, Snell: 1970, French and German tests), or whether the lining and cradle are first removed (earlier British standards and the earlier Z90.1). It is suggested that the latter methods are appropriate to the development of new materials for headgear, but that a test involving the complete helmet is more meaningful in deciding whether a given helmet is acceptable for service use.

Whilst the standards utilising complete helmets use identical strikers, namely a 60° cone with a 0.5 mm radius tip and mass of 3 kg, there is a three to one difference in impact energies (29 J for BS 2001 and 88 J for Z90.1-1971 and Snell). The pass/fail criteria also differ. Thus, the British Standard tends to reject a flexible shell whereas the Snell only rejects a shell which permits penetration as evidenced by electrical contact between striker and headform. Swearingen (1971) stresses the importance of helmet rigidity as a means for reducing skull and, therefore, brain deformation, and for increasing acceleration tolerance. Since insulation resistance *per se* is not a relevant requirement, the British test appears more logical and has the added advantage that instrumentation is external to the helmet. Furthermore, impact energies can be increased as helmet materials improve, and instead of a simple pass/fail criterion, the energy required to bring the spike to within 5 mm of the headform could be measured and used to provide a quantitative basis for comparing different helmets.

3. HARNESS STRENGTH

The tests for harness and chin strap strengths are summarised in Table 5. All the standards require specified loads to be supported by means of an artificial jaw without exceeding given elongations of the harness. Loading is either applied very slowly (British tests), or at an unspecified rate (US tests), and the required loads vary from 51 to 136 kg. Allowable displacement of the 'jaw' is about 25 mm.

All these tests are unrealistic in that the loading is quasi-static, whereas in actual use the loading would be very sudden. It seems reasonable to insist that a helmet should remain in place following at least a $-50 G_z$ head acceleration, and there would be a good argument in favour of putting this up to 400 G, since that is the tolerance level to which the impact protection has been designed. For a 1.5 kg helmet this indicates an abrupt loading of at least 75 kg (or possibly 600 kg), with displacement not exceeding 25 mm. The required load should be related to helmet weight. A suitable test should be devised.

At present there is no test method for helmet retention during crash impact. Such a test is urgently required since a protective helmet ceases to function if it comes off the head. An appropriate level of impact acceleration for this test would be the level to which the aircraft seat and harness is designed; for example, a maximum of $-40 G_x$ (Mil-S-9479B, USAF) but, ideally, all three axes of acceleration should be investigated. A second situation where helmet retention is essential is during windblast following ejection. This requires blower tunnel testing at an appropriate windspeed and rate of onset, again using a representative dummy head.

Finally, the maximum acceptable all-up weight for a helmet should be defined. Heavy helmets may offer greater impact protection, but will be less comfortable and more fatiguing to wear. New materials allow equal protection to be obtained with less weight and this trend should be encouraged. Specifying weight alone is not enough, however, for the disposition of this weight over the wearer's head is equally important. Thus, if the centre of gravity of the head plus helmet is markedly different from that of the head alone, not only will additional muscular effort be required, but dangerous neck loads could be produced during crashes or assisted escape from aircraft. A simple technique for the measurement of a helmet's centre of gravity has been reported by Aram (1970), and could be adopted as the basis for a standard test.

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TABLE 1

Current UK Standards for Protective Helmets

British Standards Institution				
Institution	BS 1869:1960	BS 2495:1960	BS 4423:1969	BS 2001:1972
Standard	Racing motor cyclists RAF Mk 1A helmet Army parachutists' helmet	Racing car drivers RAF Mk 2 and 3 helmet RAF HSAB helmet	Climbers' helmets	Motor cyclists
Application				
Method	Fixed headform	Fixed headform	Fixed headform (but dropped headform allowed)	Fixed headform or Swing-away headform
Headform	Wood in 16 sizes	Wood in 16 sizes	Wood in 16 sizes	Wood in 16 sizes
Anvil	Flat wood, 10 lbs	Flat wood, 10 lbs	Flat wood, 5 kg	Flat wood, 5 kg
Impact site	60° front and rear	60° front and rear	60° front and rear	On defined circumference or crown
Number of impacts	2 (repeated at same site if shell fractures)	2 (repeated at same site if shell fractures)	2 1 Side	1 (may be repeated at second site)
Drop height	12 ft	15 ft	8.2 ft 4.5 ft	$2.5 \times \frac{k+1}{k} \text{ m}$
Impact energy	120 ft lbf (163 J)	150 ft lbf (203 J)	90 ft lbf (122 J) 310 J	123 J
Total impact energy	Not less than 326 J	Not less than 406 J	Ambient, hot, cold, wet spray	(k = mass of helmeted head- form ÷ mass of striker)
Conditioning	Hot, cold, wet spray	Hot, cold, wet spray		123 J
Pass criteria: transmitted force	Not more than 5,000 lbf (22.3 kN)	Not more than 5,000 lbf (22.3 kN)	Not more than 4,400 lbf (19.6 kN)	Not less than 123 J
shell	Intact. Test repeated if edge of shell cracks.	Intact. Test repeated if edge of shell cracks.	Intact. No crack to extend to edge of shell.	Not more than 400 G (19.6 kN)
				Intact. Impact repeated at same site if shell fractures.

TABLE 2a.
Current US Standards for Protective Helmets

Institution	American Standards Association (now ANSI)				Snell Memorial Foundation																																											
Standard	Z90.1-1966				1970																																											
Application	Protective headgear for vehicular users. Army and Air Force helmets.				Protective headgear.																																											
Method	Dropped headform, or swing-away headform.				Dropped headform.																																											
Headform	5 kg alloy (including supporting arm), single size.				5 kg alloy (including arm), single size.																																											
Anvil	Flat or hemispherical (1.9 in. radius), steel. To weigh 5 kg when used as an impactor.				Flat or hemispherical (radius = 1.9 in.), steel.																																											
Impact site	4 sites at random above defined reference plane.				4 sites at random above defined reference plane.																																											
Number of impacts	At least 8, 4 with each anvil. 2 identical impacts to each site.				At least 8, 4 with each anvil. 2 graded impacts to each site.																																											
Impact details:	<table><tr><th colspan="2">Dropped headform</th><th colspan="2">Swing-away headform</th></tr><tr><th>Flat anvil</th><th>Hemispherical anvil</th><th>Flat anvil</th><th>Hemispherical anvil</th></tr><tr><td>6 ft (1.83 m)</td><td>54 in. (1.34 m)</td><td>175 in. (4.43 m)</td><td>131 in. (3.32 m)</td></tr><tr><td>66 ft lbf (89 J)</td><td>50 ft lbf (68 J)</td><td>160 ft lbf (217 J)</td><td>120 ft lbf (163 J)</td></tr><tr><td>116 J</td><td>88 J</td><td>123 J</td><td>92 J</td></tr><tr><td>232 J</td><td>176 J</td><td>246 J</td><td>184 J</td></tr><tr><td colspan="2">Not less than 816 J</td><td colspan="2">Not less than 860 J</td></tr></table>				Dropped headform		Swing-away headform		Flat anvil	Hemispherical anvil	Flat anvil	Hemispherical anvil	6 ft (1.83 m)	54 in. (1.34 m)	175 in. (4.43 m)	131 in. (3.32 m)	66 ft lbf (89 J)	50 ft lbf (68 J)	160 ft lbf (217 J)	120 ft lbf (163 J)	116 J	88 J	123 J	92 J	232 J	176 J	246 J	184 J	Not less than 816 J		Not less than 860 J		<table><tr><th colspan="2">Either anvil</th></tr><tr><th>1st impact</th><th>2nd impact</th></tr><tr><td>8 ft (2.44 m)</td><td>6 ft (1.83 m)</td></tr><tr><td>88 ft lbf (119 J)</td><td>66 ft lbf (89 J)</td></tr><tr><td>155 J</td><td>116 J</td></tr><tr><td>271 J</td><td></td></tr><tr><td colspan="2">Not less than 1,084 J</td></tr></table>		Either anvil		1st impact	2nd impact	8 ft (2.44 m)	6 ft (1.83 m)	88 ft lbf (119 J)	66 ft lbf (89 J)	155 J	116 J	271 J		Not less than 1,084 J	
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Conditioning	Ambient, hot, cold, water soak				Ambient, hot, cold, water soak																																											
Pass criteria - force	Not more than 400 G, or more than 200 G for more than 2 msec, or more than 150 G for more than 4 msec.				Not more than 300 G.																																											

TABLE 3
Standards Proposed by BSI and ANSI for UK and US Air Force Helmets

Institution	British Standards Institution	American National Standards Institute	Comments
Standard	BS 0000	Z90. 1-1971	See Rayne, 1969.
Method	Swing-away headform with accelerometer in striker.	Dropped headform with accelerometer.	
Headform	Wood in 5 sizes.	Alloy in single size, 5 kg	Effect of composition needs investigation. ANSI can only evaluate medium size helmets.
Anvil	Flat or hemispherical (radius = 48mm) 5 kg. Material not stated.	Flat or hemispherical (radius = 4.8 cm), steel.	Curved impactor requires stronger shell for similar impact.
Impact site	Within 80° solid angle of central axis based on c of g of head.	Above a plane lying 60 mm above and parallel to Reid's baseline.	ANSI requirement covers more headform area.
Number of impacts	Double impacts at a minimum of two sites.	Minimum of eight, with two identical impacts at each of four sites, two with each anvil.	Affects design of energy absorbing system.
Kinetic energy of impact	Dependent upon mass of helmet and headform.	89 J for flat, and 68 J for hemispherical anvil, discounting helmet weight.	Calls for different capabilities of energy absorbing system and shell. ANSI penalises heavy helmets since kinetic energy of helmet is added to that of the falling headform.
Energy of impact	122J for both anvils, but reduced to 108J for an extended area to rear of helmet when using hemispherical anvil.	116 J and 88 J respectively, assuming helmet weight of 1.5 kg.	
Impact energy per site	Generally 244J.	232 J and 176 J respectively, for 1.5 kg helmet.	No significant difference.
Total impact energy	Generally 488J.	At least 816 J for 1.5 kg helmet.	
Conditioning	Hot 50°C for 4 to 24 hr Cold -20°C for 4 to 24 hr Wet. Immersed in water at 20°C for 4 to 24 hr.	Hot 50°C for 4 to 24 hr Cold -10°C for 4 to 24 hr Wet. Immersed in water at 25°C for 4 to 24 hr.	
Pass/fail criteria	First test loadings applied within 3 min. Deceleration of striker not to exceed 400 G.	Tests to be completed within 5 min. Deceleration of headform not to exceed 400 G, or 200 G for more than 2 msec, or 150 G for more than 4 msec.	Shell temperatures at impact may differ. Time element makes US standard more exacting, but physiological basis for either criteria is vague. (See Swearingen, 1971)

TABLE 4.
Tests Used to Determine Penetration Resistance of Protective Helmets

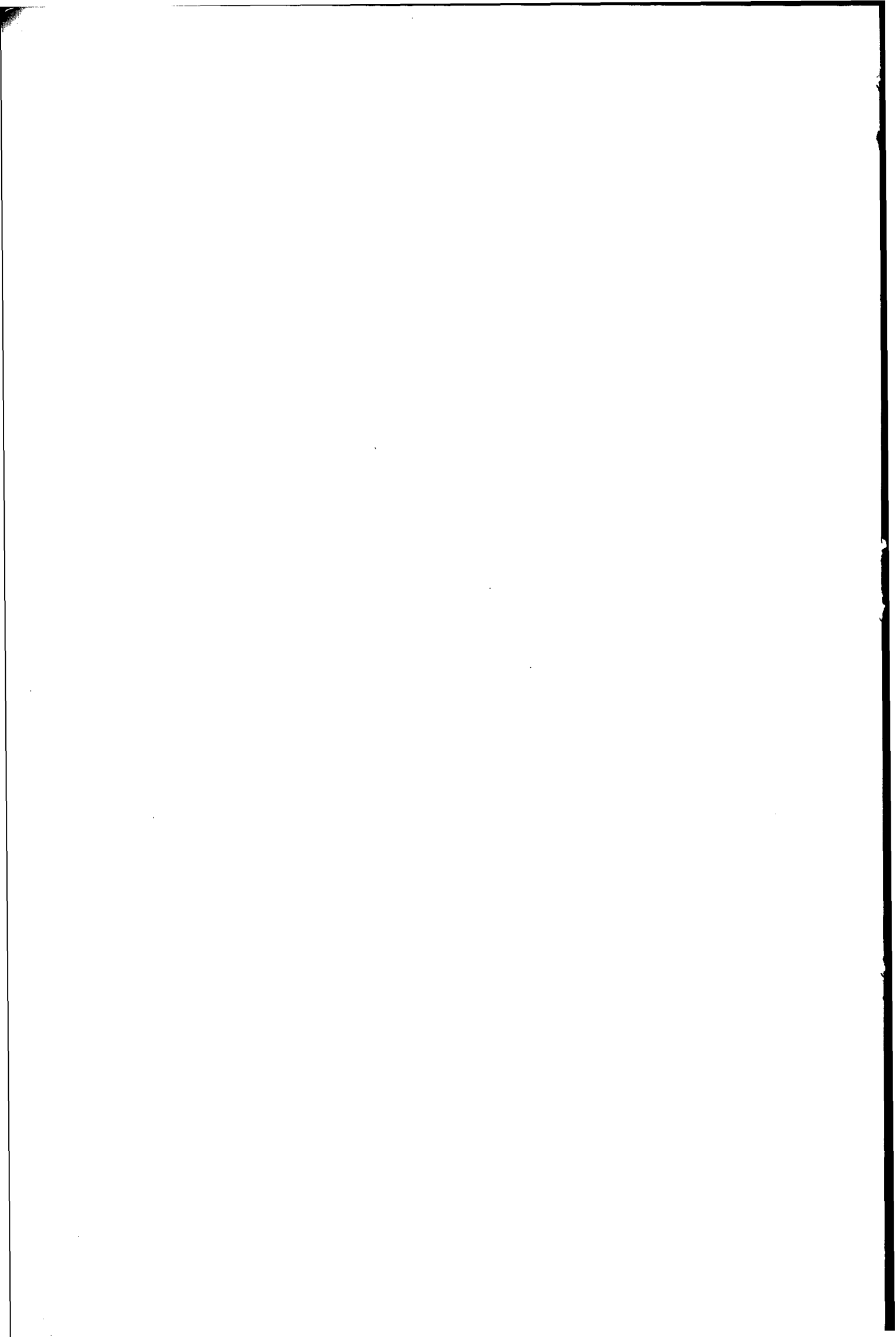
Nation	UK	US		Germany	France
Standard	BS 1869:1960 BS 2495:1960 BS 4423:1969	BS 2001:1972	Z90.1-1966	Snell 1970 (Z90.1-1971)	
Method	Helmet with cradle and lining removed, placed on headform with central cavity and impacted with a spike. Deflection of shell recorded from within cavity.	Helmet placed on headform. Spike placed on helmet and impacted with a dropped weight. Depth of penetration recorded externally.	Helmet with cradle and lining removed, placed on headform with central cavity and impacted with a spike. Deflection of shell recorded from within cavity.	Helmet with cradle maximally relaxed, placed on alloy headform and impacted with a spike. Electrical resistance, spike to headform, recorded.	Helmet mounted on headform and impacted with a steel ball. Damage noted.
Headform	Wooden headform with central cavity 45 mm in diameter.	Standard wooden headform as used in impact tests.	Alloy headform with central cavity 4.5 cm in diameter.	Standard headform covered by electrically conductive material.	Probably wooden.
Impactor	1.81 kg steel spike, 32 mm diameter with 60° conical point. Tip radius 0.51 mm.	Spike weight 0.3 kg, 40 mm high 60° cone with 0.5 mm radius tip of hardness 45-50 Rockwells. Dropped weight 3 kg	3 kg with 60° conical point. Tip radius 0.5 mm and hardness 60 Rockwells.	3 kg with 38 mm tall 60° conical point. Tip radius 0.5 mm and hardness 60 Rockwells.	3 kg steel ball. Radius estimated to be 4.5 cm.
Impact — height	3 ft (0.91 m)	1 m	1 m	3 m	0.95 m (1 m from centre of ball to shell).
— site	Centre of crown over headform cavity.	Above defined circumference.	Centre of crown over headform cavity.	Above reference plane. (Two impacts at least 3" apart, clear of previous impact sites.)	Centre of crown.
— energy	16 J	29 J	29 J	88 J	28 J
Conditioning	As for impact tests.	As for helmet giving worst impact response.	As for impact tests.	As for impact tests.	Not known.
Pass/fail criteria	Maximum instantaneous vertical deflection not to exceed 9.5 mm. Inner surface of helmet not to be pierced.	Distance between point of spike and shell must never be less than 5 mm	Maximum instantaneous vertical deflection not to exceed 10 mm. Shell not to be pierced as recorded electrically.	Helmet rejected if demonstrable electrical contact between spike and headform.	Shell must remain intact with no permanent deformation and no displacement of internal structures.

TABLE 5.

Standards For Harness Strength

Standard	BS 1869:1960, 2495:1960, 4423:1969	
Method	Helmet supported by brim. Chin strap loaded through special hanger by 4.5 kg for ½ to 1 min. Load increased over 30 sec to 90.7 kg and left for 2 min.	
Pass/fail criteria	Vertical movement of hanger following second load must not exceed 31.8 mm.	
Standard	BS 2001:1972	
Method	1. Helmet on headform. Chin strap loaded through two 12.5 mm dia. rollers at 75 mm centres by 4.6 kg, and load increased over 30 sec to 51 kg and maintained for 2 min.	2. Helmet on headform supported by brim. Load of 102 kg applied to harness attachment points over 30 sec.
Pass/fail criteria	Vertical displacement of loading weight must not exceed 25 mm.	No breakage or tearing at attachment points.
Standard	Z90.1-1966 (1971) and Snell: 1970	
Method	1. Helmet on headform. Chin strap loaded through two 12.7 mm dia. rollers at 76 mm centres by weight of 136 kg (after 23 kg preload).	2. Chin strap tested for ultimate strength and for elongation under tension.
Pass/fail criteria	Load to be supported without parting or displacement in excess of 25.4 mm.	

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